International Journal of Energy and Environmental Engineering
ISSN: 2008-9163 eISSN:2251-6832
Vol.2 / No.4 (pp.1-12) / Fall 2011

Performance of a photovoltaic/thermal solar air heater: Effect of vertical fins on a double pass system

[1]Marc A. Rosen, [2]Rakesh Kumar

[1, 2]Faculty of Engineering and Applied Sciences University of Ontario Institute of Technology
2000 Simcoe Street North oshawa, Ontario, L1H 7K4, Canada

Received: 9 Sept. 2011 Accepted: 15 Oct. 2011

ABSTRACT

The steady state effect of vertical fins is assessed on a photovoltaic/thermal solar air heater having a double pass configuration in which fins are placed in the lower channel perpendicular to the direction of air flow. Air passes through the upper channel of the air heater and before passing in the opposite direction through the lower channel. The effects of design, climatic and operating parameters are evaluated on temperatures, efficiencies and other parameters. For fixed operating conditions, fins are observed to increase heat transfer area and rate, reduce cell temperature about 16°C, and improve thermal and electrical efficiencies. Higher packing factors are advantageous as they increase electrical output per collector area and reduce cell temperature.

Keywords

solar energy, air heating, photovoltaic/thermal, fin, thermal, efficiency

1. Introduction

The utilization of solar energy depends highly on the technology's performance, economics, efficiency, reliability and durability. Two main types of solar energy technology and many advances have been reported in recent years for each:

- Solar thermal energy systems have improved in reliability and efficiency, with efficiencies of 40-60% typical for low and medium temperature applications [1].
- Solar photovoltaic (PV) energy systems have achieved significant reductions in module prices [2].

However, improvements are still actively sought, as the cost of production of PV power remains considerably higher than the generation of solar thermal energy, while the nominal efficiency of mono-crystalline silicon based PV modules is still relatively low, at around 18% [3]. Photovoltaic/thermal (PV/T) solar collectors combine these two solar technologies to generate thermal and electrical energy simultaneously, often more cost effectively that is the case for separate systems. The integration of solar and PV systems also often reduces operating cell temperatures, enhancing performance and efficiency. Interest in solar PV/T technology has correspondingly increased notably over the last decade. The application of PV/T systems for air heating as well as electricity generation is of significant potential, given the large requirement for air heating in many countries.

Improvements in PV/T systems are sought to enhance their advantages, for both general applications and air heating. The present investigation is one such effort, and examines the potential benefits of adding vertical fins to a PV/T solar air heater having a double pass configuration. The main objective of this investigation is to better understand the impacts of double-pass configurations and fins on the performance of PV/T solar air heaters. This work extends a previous analysis by the present authors of the effects of fins on

Corresponding author: Marc A. Rosen (e-mail: marc.rosen@uoit.ca)

PV/T solar air heaters [4]. It is anticipated that the results will assist designers and users of the technology, and help in expanding its use.

2. Background

PV/T systems have been increasingly investigated in recent years as researchers seek to enhance the performance of such systems. Many reviews of the status and advances of the technology have been published [5-11], and examinations of potential improvements of PV/T solar energy systems [12-14].

Numerous studies of PV/T systems for air heating have been reported in recent years, aimed at better understanding the technology and improving its performance and characteristics, including a review of the status of the technology [15].

Some of these studies have involved experimental work. For instance, Tripanagnostopoulos et al. [16] constructed and field tested PV/T collector systems with both water and air as the heat transfer fluids, considering covered and uncovered collectors. In most of these investigations the collector consisted of a single-pass air heater with the air flow under the absorber surface and above the metallic back plate. The performance of these PV/T collectors increased through the use of diffuse reflectors made of flat aluminum sheets.

Many analytical and computational investigations have also been reported on PV/T systems for air heating. Some notable examples are as follows:

- Garg and Adhikari [17] simulated the performance of PV/T air heating collectors with single and double glass configurations. The authors used the analytical solution of a differential equation that yields the air temperature in the fluid flow direction.
- Cox and Raghuraman [18] sought increases in the solar absorptance and reductions in the infrared emittance of flat plate air PV/T collectors, through computer simulations.
- Kalogirou [19] performed PV/T system simulations using TRNSYS. An optimum flow rate for the PV/T system was found to be 25 l/h for a PV/T collector area of 5.1 m^2.

To increase the heat transfer rate from absorber surface to air, many modifications have been proposed in the design of PV/T air collectors. Potentially beneficial modifications include changing the air movement path, using multiple-pass air flow configurations, using corrugated absorbers and adding fins to enhance heat transfer [20,21]. Several studies of the benefits of such modifications have been reported, e.g., the improved performance due to the enhanced cooling of photovoltaic cells has been studied for PV/T double-pass air heaters relative to single-pass units [22]. Various other studies of the effects of fins in solar PV/T systems have been reported [12-14,23-30], including air a preliminary analysis of the effect of fins on a PV/T solar air heater was recently carried out by the present authors [4].

3. Base System

The assessed PV/T solar air heater with two air passes is shown in Fig. 1, and some corresponding parameter values are listed in Table 1. Solar radiation incident on the upper glass cover is transmitted to the absorber surface, where a part is converted to electricity by the PV cells and part is converted to thermal energy. Most of the heat collected by the absorber/cells is transferred to the flowing air in the upper and lower channels, with a small part lost to the surroundings. The length and width of the air heater in Fig. 1 are both 1 m for both channels. The heights of the upper and the lower channels are 10 cm and 3 cm, respectively, and the system does not incorporate fins.

4. Modified System with Fins

The same system in Fig. 1 but with fins, which is utilized as the modified case in the present investigation, is illustrated in Fig. 2. Some corresponding parameter values are listed in Table 2. The two configurations in Figs. 1 and 2 have the same component shapes and dimensions, except for the bottom surface of the absorber where vertical fins are added in Fig. 2. The height and thickness of each fin is 2.5 cm and 0.1 cm, respectively, and the number of fins is taken to be 24 per meter length of collector based on the results of Garg et al. [20]

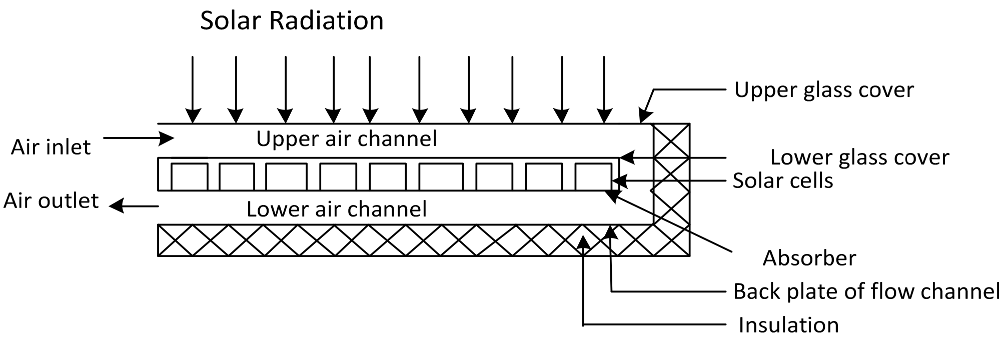

Fig. 1: Cross-section of double-pass PV/T solar air heater (base case)

Table 1: Values of dimensions for the base and modified PV/T cases

Component	Dimension	Value (m)
Air heater	Length	1.0
	Width	1.0
Upper channel	Height	0.10
Lower channel	Height	0.03

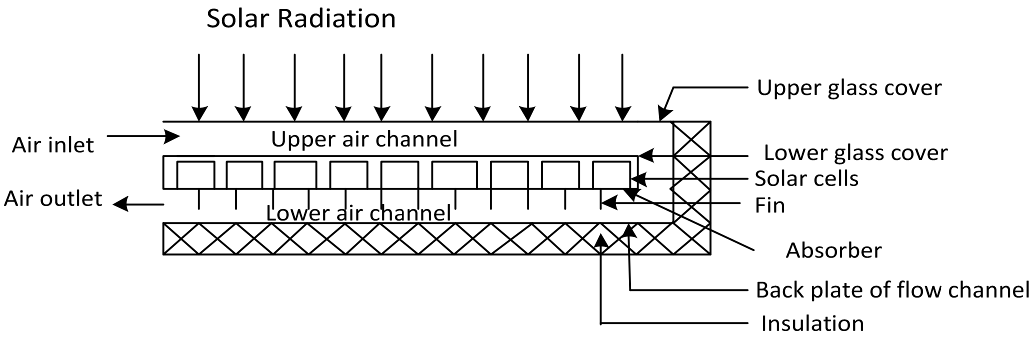

Fig. 2: Cross-section of double-pass PV/T solar air heater with fins (modified case)

Table 2: Values of fin dimensions for the modified PV/T case

Dimension	Value (m)
Height	0.025
Thickness	0.0001

5. Analysis Assumptions and Simplifications

Several assumptions and simplifications are made in the analyses:

- The effects of fins are assumed to be assessable based on steady state performance. Thus, transient effects are neglected and steady state energy balances are determined for the PV/T solar air heaters and their components.
- The air temperature is assumed to vary only along the air heater length.
- Temperature variations are assumed negligible for the upper glass cover, the lower glass cover and the back plate in the direction of air flow.
- The thermal capacity is neglected for each component of the air heater.

- Thermophysical properties of the air heater are assumed constant over the operating temperature range of the air heater.
- The mean absorber surface temperature is assumed equal to the PV cell temperature, as the incident solar irradiation and optical properties of the absorber and photovoltaic cells are assumed identical.

6. Energy Balances

Steady-state energy balances are expressed for components of the base case and modified PV/T solar air heaters.

6.1 Glass covers

A steady-state energy balance for the upper glass cover can be formulated as follows:

$$l_{g2} + h_{rg1g2}(T_{g1} - T_{g2}) = h_{rg2s}(T_{g2} - T_s) + h_{cg2w}(T_{g2} - T_a) + h_{cg2f1}(T_{g2} - T_{f1}) \tag{1}$$

Here, I_t is the total solar radiation incident on the upper glass, and T_{g1}, T_{g2}, T_s T_a, and T_{f1} are the temperatures of the lower glass, the upper glass, the sky, the ambient air, and the air in the upper channel, respectively. Also, h_{rg1g2} is the radiative heat transfer coefficient from the lower glass to upper glass, h_{rg2s} is the radiative heat transfer coefficient from the upper glass to sky, h_{cg2w} is the wind induced heat transfer coefficient from the upper glass to ambient air, and h_{cg2f1} is the convective heat transfer coefficient from the upper glass to air.

Similarly, a steady-state energy balance for the lower glass cover can be expressed as follows:

$$l_{g1} + h_{rpg1}(T_p - T_{g1}) = h_{rg1g2}(T_{g1} - T_{g2}) + h_{cg1f1}(T_{g1} - T_{f1}) \tag{2}$$

where h_{rpg1} is the radiative heat transfer coefficient from the absorber surface to the lower glass, and T_p is the temperature of the absorber surface.

6.2 Air in channels

A steady-state energy balance for the air in the upper channel can be formulated as follows:

$$\frac{\dot{m}_{cf}}{w_1}\frac{dT_{f2}}{dx} = h_{cg1f1}(T_{g1} - T_{f1}) + h_{cg2f1}(T_{g2} - T_{f1}) \tag{3}$$

Where $\dot{m}$ is the air flow rate and c_f is its specific heat capacity Also, w_1 is the width of the upper air channel, and h_{cg1f1} is the convective heat transfer from the lower glass cover to air.

Similarly, a steady-state energy balance for the air in the lower channel follows:

$$-\frac{\dot{m}_{cf}}{w_2}\frac{dT_{f2}}{dx} = h_{cpf2}K_1(T_p - T_{f2}) + h_{cg2f2}(T_{s2} - T_{f2}) \tag{4}$$

where w_2 is the width of lower channel, h_{cs2f2} is the convective heat transfer from the back plate to the air in the lower channel, and T_{f2} is the temperature of air in the lower channel.

6.3 Absorber/cell surface

A steady-state energy balance for the absorber/cell surface can be expressed as follows:

$$l_p(1-P) + l_{pv}P(1-\eta_{el}) = h_{rpg1}(T_p - T_{g1}) + h_{cpf2}K_1(T_p - T_{f2}) + h_{rps2}K_2(T_p - T_{s2}) \tag{5}$$

where I_p and I_{pv} are the quantities of solar irradiance absorbed by the absorber and photovoltaic cells, respectively, P is the packing factor of photovoltaic module, which is the fraction of the absorber surface occupied by the photovoltaic cells, η_{el} is the electrical efficiency, h_{cpf2} is the convective heat transfer coefficient from the absorber surface to air in the lower column, h_{rps2} is the radiative heat transfer coefficient from the absorber surface to the back plate, and T_{s2} is the temperature of the back plate.

The factors K_1 and K_2 are defined as [20] follows:

$$K_1 = \eta_0\left(A_0/A\right) \tag{6}$$

$$K_2 = F_0\left(A_0/A\right) \tag{7}$$

Where

$$A_0 = A + A_{fin} \tag{8}$$

$$\eta_0 = 1 - \frac{A_{fin}}{A_0}(1 - \eta_{fin}) \tag{9}$$

$$\eta_{fin} = \frac{tanh\, mL_2}{mL_2} \tag{10}$$

$$m = \sqrt{\frac{2h_{cpf2}}{k_{fin} w_{fin}}} \tag{11}$$

$$F_0 = \frac{1}{\frac{1}{\varepsilon_p} + \frac{A_0}{A}\left(\frac{1}{\varepsilon_{s2}} - 1\right)} \tag{12}$$

Here, A is the area of the bottom surface of the absorber without fins, A_{fin} is area of the fins, L_1 is the height of the fins, η_o is the fin effectiveness, η_{fin} is the fin efficiency, k_{fin} is the thermal conductivity of the fin material, w_{fin} is fin thickness, F_0 is the shape factor for radiative heat transfer from the bottom of the absorber surface to the the back plate, ε_p and ε_{s2} are the emissivities of the absorber surface and the back plate, respectively, and h_{cpf2} is the convective heat transfer coefficient from the absorber to air in the lower channel.

6.4 Back plate

A steady-state energy balance for the back plate can be formulated as follows:

$$h_{rps2} K_2 (T_p - T_{s2}) = h_{cs2f2}(T_{s2} - T_{f2}) + U_b (T_{s2} - T_a) \tag{13}$$

where U_b is the bottom heat transfer coefficient and T_a is the ambient air temperature.

7. Analysis

Eliminating T_{g1}, T_{g2}, T_p and T_{s2} from Equations (3) and (4) by rearranging Equations (1), (2), (5) and (13) yields two first-order linear differential equations:

$$\frac{dT_{f1}}{dx} = X_1 + X_2 T_{f1} + X_3 T_{f2} \tag{14}$$

$$\frac{dT_{f2}}{dx} = Y_1 + Y_2 T_{f1} + Y_3 T_{f2} \tag{15}$$

where X_1, X_2, X_3, Y_1, Y_2 and Y_3 are constants which can be algebraically evaluated. Solving Equations (14) and (15) yields air temperatures as function of x in the direction of air flow in the upper and the lower channels:

$$T_{f1}(x) = \frac{1}{Y_2}\{(N_1 - Y_3)M_1 \exp(N_1 x) + (N_2 - Y_3)M_2 \exp(N_2 x) - Y_3 S - Y_1\} \tag{16}$$

$$T_{f2}(x) = M_1 \exp(N_1 x) + M_2 \exp(N_2 x) + S \tag{17}$$

where

$$S = \left(\frac{Y_2 X_1 - X_2 Y_1}{X_2 Y_3 - Y_2 X_3}\right) \tag{18}$$

$$N_1 = \frac{(x_2 + Y_3) + \sqrt{(X_2 - Y_3)^2 + 4X_3 Y_2}}{2} \tag{19}$$

$$N_2 = \frac{(x_2 + Y_3) - \sqrt{(X_2 - Y_3)^2 + 4X_3 Y_2}}{2} \tag{20}$$

$$M_1 = \frac{(Y_3 S + Y_1 + Y_2 T_{in})}{(N_1 - Y_3)} - \frac{(N_2 - Y_3)}{(N_1 - Y_3)} M_2 \tag{21}$$

$$M_2 = \left\{\frac{(SY_3 + Y_1 + Y_2 T_{in})(N_1 - Y_3 - Y_2)\exp(N_2 L) - (SY_3 + Y_1 + Y_2 S)(N_1 - Y_3)}{(N_2 - Y_3)(N_1 - Y_3 - Y_2)\exp(N_1 L) - (N_1 - Y_3)(N_2 - Y_3 - Y_2)\exp(N_2 L)}\right\} \tag{22}$$

The following boundary conditions are used to determine of N_1, N_2, M_1 and M_2:

$$T_{f1} = T_{in}(at\ x = 0) \tag{23a}$$

$$T_{f1} = T_{f2}(at\ x = L) \tag{23b}$$

where T_{in} is the inlet air temperature of for the upper air channel, and L is the air heater length.

The radiative heat transfer coefficients in Equations (1), (2), (5) and (13) are evaluated using relations in Holman [31], while the forced convective heat transfer coefficients for the air flow in the upper and lower channels, which is turbulent for the range of flow rates encountered in the present investigation, are calculated using a correlation derived from the data of Kays [32]. The packing factor is taken to be 0.50 arbitrarily dividing the absorber surface equally for thermal and electrical output.

8. Efficiencies

8.1 Energy and electrical efficiencies

The energy (or thermal) efficiency of the PV/T air heater is expressed as:

$$\eta_{th} = \frac{\dot{m} c_f (T_{fo} - T_{fi})}{A_c I_t} \quad (24)$$

Here, $\dot{m}$ is the air flow rate, c_f is the specific heat of air, and T_{fi} and T_{fo} are the air temperatures at the entrance of the upper channel and the outlet of the lower channel, respectively.
The electrical efficiency of the PV cells can be evaluated as follows [33]:

$$\eta_{el} = n_{op} [1 - 0.0045 (T_{pm} - T_{ref})] \quad (25)$$

where η_{op} is the nominal efficiency of the photovoltaic cell at the reference temperature T_{ref}, and η_{el} is the efficiency of the photovoltaic cell at the mean absorber temperature T_{pm}. By integrating $T_p(x)$ in the direction of air flow, the mean absorber temperature is expressed as:

$$T_{pm} = \frac{\int_o^L T_p(x) dx}{\int_o^L dx} \quad (26)$$

8.2 Overall Efficiency

The economic value of electrical and thermal energy generally differs, since electricity is high grade energy and heat at near-environmental temperatures is low grade energy. Thus it is unreasonable to simply sum them to obtain an overall efficiency. Introducing the equivalent thermal electrical efficiency [34, 35] the conversion of the electrical efficiency (of PV cells) to an equivalent energy efficiency for a thermal power plant. Then, the overall efficiency of PV/T air heater is calculated as:

$$\eta_{total} = \frac{\eta_{el}}{c_{f1}} + \eta_{th} \quad (27)$$

where c_{f1} is the conversion factor of the thermal power plant, taken to be 0.38 here.

9. Results and Discussion

The performance is evaluated for the base case PV/T solar air heater as well as the modified PV/T solar air heater with fins. The effects of system, climatic and operating parameters and packing factor are considered.

9.1 Results for base case

Parametric variations for modified designs of the PV/T solar air heater are presented in Figs. 3 to 7.

9.1.1 Effects of solar irradiance and air mass flow rate on temperatures

The effect of solar irradiance and air mass flow rate on the temperature rise of air as it passes through the air heater ($T_{fo} - T_{fi}$) is shown in Fig. 3a, and on the absorber/cell temperature is shown in Fig. 3b. The air temperature increase with solar irradiance is almost linear and is somewhat more significant at lower flow rates (0.03 kg/s) than at higher flow rates. The increase in absorber/cell temperature with solar irradiance is more significant at low flow rates (0.03 kg/s) than high flow rates (0.15 kg/s). The absorber/cell temperature increases almost linearly with solar irradiance on the collector surface. The increase in the absorber/cell temperature at low air flow rates (0.03 kg/s) reduces the energy and electrical efficiencies of the PV/T air collector (as seen subsequently in Fig. 4). Note that a low cell temperature increases the electrical outputs and the inlet air temperature. The thermal output of air heater is useful only for low temperature applications or pre-heating of air.

9.1.2 Effects of solar irradiance, air mass flow rate and temperatures on efficiencies

The effect of solar irradiance and air mass flow rate on the PV/T energy efficiency is shown in Fig. 4a and on the PV/T electrical efficiency is shown in Fig. 4b. Also, the effects of air mass flow rate and the ratio of the air temperature rise to the total solar irradiance on the PV/T energy efficiency are shown in Fig. 5. The variation in energy efficiency with solar irradiance is seen in Fig. 4a to be minor. For lower flow rates (0.03 kg/s) the energy efficiency decreases marginally with solar irradiance, while for higher flow rates the energy efficiency increases slightly. Increasing solar irradiance is seen in Fig. 4b to reduce the electrical efficiency, mainly because it increases the absorber/cell temperature.

The PV/T energy efficiency curves in Fig. 5, which illustrate the effects of air mass flow rate and ratio of the air temperature rise to total solar irradiance, provide information on the maximum thermal heat attainable from the PV/T

air heater for various flow rates and inlet air temperatures. The maximum thermal output from the PV/T collector corresponds to an air mass flow rate of around 0.12 to 0.15 kg/s. Also, the solar air heater system is not as efficient for high inlet temperatures.

9.1.3 Effect of channel depths on overall efficiency

The effects of upper and lower channel depths on the PV/T overall efficiency are shown in Fig. 6. The convective heat transfer rates to air vary with channel depths, affecting the air heater overall efficiency. The effect of depth is observed to be more significant for the lower channel than the upper channel.

9.1.4 Effect of packing factor on efficiencies and temperatures

The effects are shown in Figure 7 of packing factor on PV/T energy, electrical and overall efficiencies and on the rise in air temperature. As the packing factor, which denotes the fraction of absorber area dedicated to photovoltaic cells, increases from about 0.4 to 1.0, the PV/T electrical efficiency increases by 5%, and the PV/T overall efficiency by 17%. The packing factor affects the electrical output of the solar PV/T collector significantly, with most of the efficiency increase attributable to the increased electrical output per unit collector area. The thermal energy output of the air heater decreases with packing factor, as an increasing portion of the collector surface area is used for electricity generation. Thus, the rise in air temperature is observed in Fig. 7 to decrease with increasing packing factor.

9.2 Comparison of results for base and modified cases

In this section, the effects of fins on efficiencies and temperatures are presented. The energy, electrical and overall efficiencies are illustrated in Table 3 for the solar PV/T system without fins (base case) and with fins (modified case), and the results for the base and modified cases are compared. To improve understanding, the differences in the air and cell temperatures for the base and modified cases are also indicated in that figure. The thermal and electrical efficiencies are low for the base case system and the cell temperature is relatively high. The effect of fins on the back side of the absorber surface is clear in Table 3, with the addition of fins increasing the PV/T energy, electrical and overall efficiencies. Adding fins also increases the surface area of the system absorber which, in turn, increases the heat transfer from the surface. This phenomenon reduces the absorber/cell temperature

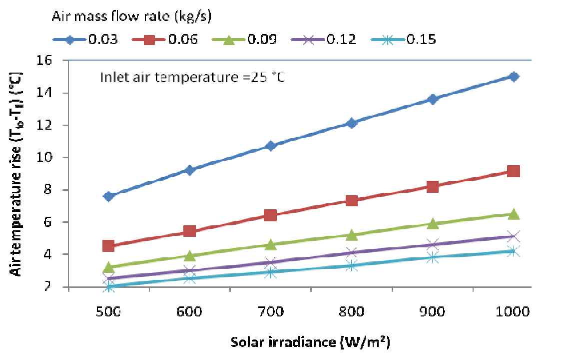

Fig. 3a: Variation in air temperature rise in the air heater with solar irradiance and air mass flow rate

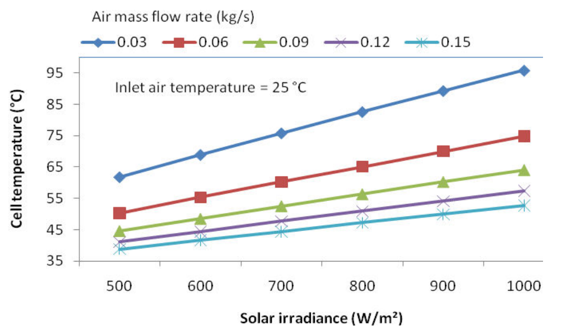

Fig. 3b: Variation in PV cell temperature of the PV/T air heater with solar irradiance and air mass flow rate

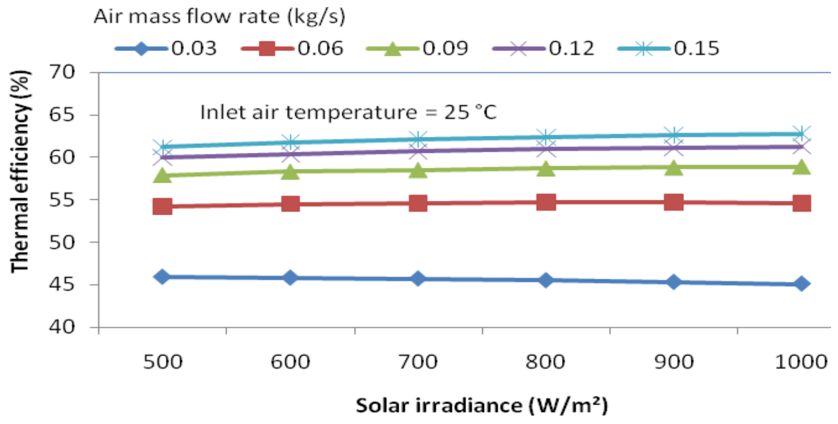

Fig. 4a: Variation in air heater energy efficiency with solar irradiance and air mass flow rate

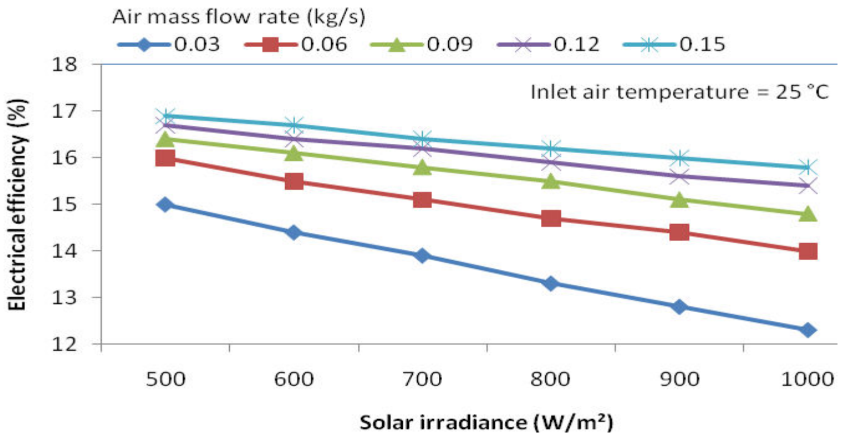

Fig. 4b: Variation in PV/T air heater electrical efficiency with solar irradiance and air mass flow rate**.**

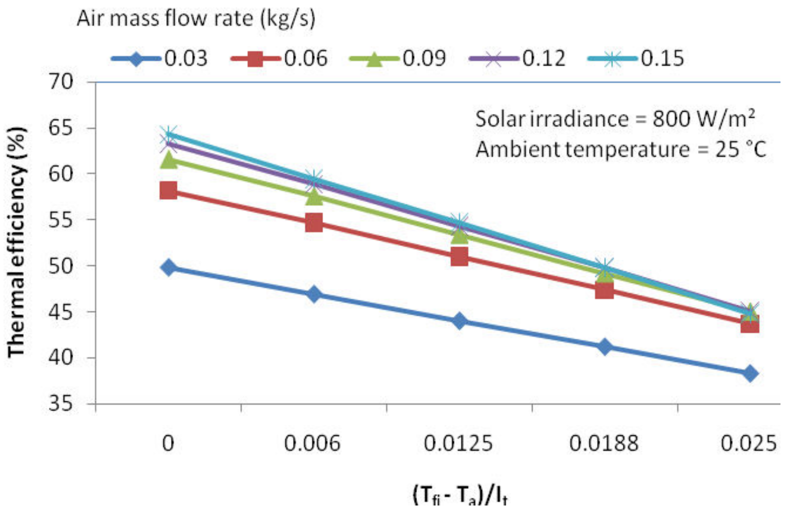

Fig. 5: Variation in PV/T air heater energy efficiency with air mass flow rate and ratio of air temperature rise to total solar irradiance.

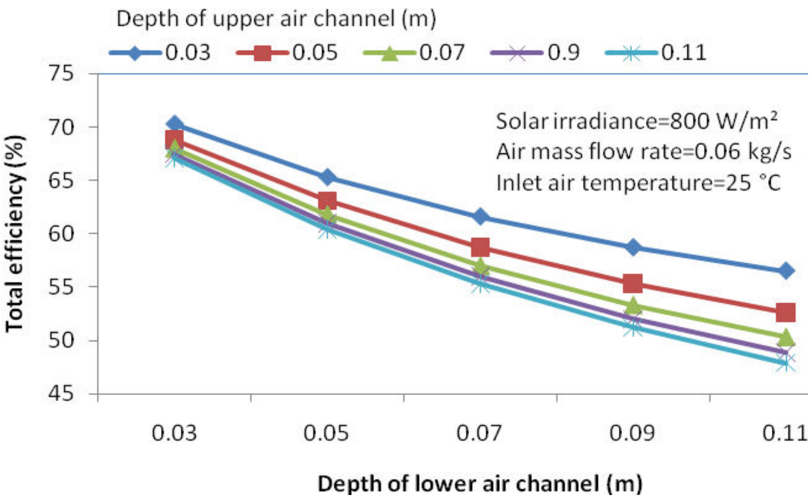

Fig. 6: Variation of PV/T air heater overall efficiency with depths of channels

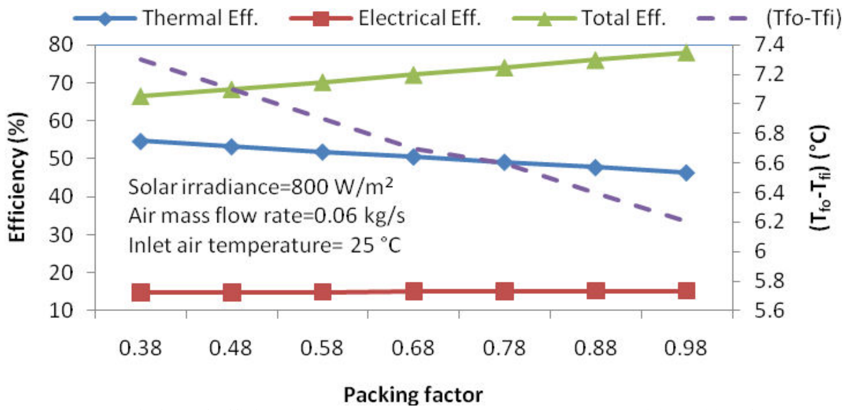

Fig. 7: Variation of efficiencies and rise in air temperature ($T_{fo} - T_{fi}$) with packing factor.

Table 3: Efficiencies and temperatures for the base and modified solar PV/T air heating systems*

Parameter	Base case (without fins)	Modified case (with fins)	Change (from base to modified case)
Efficiencies (%)			
Energy	48	55	7
Electrical	14	15	1
Overall	58	66	8
Temperatures (°C)			
Cell surface	83	66	–17
Rise	6	7.5	1.5

* For a solar irradiance of 800 W/m^2, and an air mass flow rate of 0.06 kg/s and inlet temperature of 25°C.

1-Further analyses were carried out to determine the dependence of the results on fin configuration (height and thickness as well as spacing). It was observed that the primary results presented do not change significantly with moderate variations in these parameters, providing the variations do not inhibit the air flow.

10. Conclusions

The addition of vertical fins perpendicular to the direction of air flow to the lower channel of a PV/T solar air heater having a double pass configuration enhances energy performance. The analysis highlights the significance of design, climatic and operational parameters on thermal and electrical outputs and provides useful insights into the thermal and electrical behaviour of a double-pass air heater with vertical fins in the lower air channels. The addition of fins increases the heat transfer area and rate, reduces the cell temperature, and improves the energy and electrical efficiencies. It is observed that energy efficiency varies nearly linearly with both solar irradiance and inlet air temperature, the PV/T electrical efficiency is significantly affected by absorber/cell temperature, the depth of the upper and lower channels are significant although the lower channel depth affects heat transfer to air more, and higher packing factors increase unit electrical output per collector area and reduce the cell temperature.

Nomenclature

A	Absorber area [m^2]
A_{fin}	Fin area [m^2]
c_f	Specific heat of air [J/kg-K]
c_{f1}	Conversion factor of the thermal power plant
h	Heat transfer coefficient [W/m^2-K]
I	Solar irradiance [W/m^2]
k_b	Bottom insulation thermal conductivity [W/m-K]
k_{fin}	Fin thermal conductivity [W/m-K]
L	Air heater length [m]
T	Temperature [ºC]
$\dot{m}$	Air mass flow rate [kg/s]
P	Packing factor
U	Bottom heat transfer coefficient [W/m^2-K]
w_1	Upper air channel width [m]
w_2	Lower air channel width [m]
w_{fin}	Fin thickness
x	Distance along heater

Greek letters

η_{el}	PV cell electrical efficiency
η_{total}	PV/T air heater overall (total) efficiency
η_o	Fin effectiveness
η_{op}	PV cell nominal efficiency
η_{fin}	Fin efficiency

Subscripts

a	ambient
b	bottom surface
cg1f1	convective lower glass to air
cg2f1	convective upper glass to air
cg2w	convective upper glass to ambient
cpf2	convective absorber surface to air in lower channel
cs2f2	convective back plate to air in lower channel
El	electrical
f1	air in upper channel
f2	air in lower channel
fi	air at inletfo air at outlet
g1	lower glass
g2	upper glassin inlet
p	absorber surface
pm	mean absorber temperature
ref	reference temperature
Pv	photovoltaic module
rg1g2	radiative lower glass to upper glass
rg2s	radiative upper glass to sky
rpg1	radiative absorber to lower glass
s	sky
s2	back plate

Acknowledgements

Financial support was provided by the Natural Sciences and Engineering Research Council of Canada.

References

[1] Thirugnanasambandam M, Iniyan S, Goic R. A review of solar thermal technologies. Renewable and Sustainable Energy Reviews 2010;14:312–322.

[2] Branker K, Pearce JM. Financial return for government support of large-scale thin-film solar photovoltaic manufacturing in Canada.

[3] Energy Policy 2010;38:4291-4303.

[4] Liou HM. Overview of the photovoltaic technology status and perspective in Taiwan. Renewable and Sustainable Energy Reviews 2010;14:1202-1215.

[5] Kumar R, Rosen MA. Performance evaluation of a double pass PV/T solar air heater with and without fins. Applied Thermal Engineering 2011;31:1402-1410.

[6] Chow TT. A review on photovoltaic/thermal hybrid solar technology. Applied Energy 2010;87:365-379.

[7] Ibrahim A, Yusof Othman M, Hafidz Ruslan M, Mat S., Sopian K. Recent advances in flat plate photovoltaic/thermal (PV/T) solar collectors. Renewable and Sustainable Energy Reviews 2011;15:352-365.

[8] Chen H, Riffat SB. Development of photovoltaic thermal technology in recent years: a review. Int. J. Low-Carbon Tech. 2011;6:1-13.

[9] Ramos F, Cardoso A, Alcaso A. Hybrid photovoltaic-thermal collectors: a review. Emerging Trends in Technological Innovation 2010; 314: 477-484.

[10] Riffat SB, Cuce E. A review on hybrid photovoltaic/thermal collectors and systems. Int. J. Low-Carbon Tech. 2011;6:212-241.

[11] Charalambous PG, Maidment GG, Kalogirou SA, Yiakoumetti K. Photovoltaic thermal (PV/T) collectors: a review. Applied Thermal Engineering 2007;27:275-286.

[12] Tripanagnostopoulos Y. Aspects and improvements of hybrid photovoltaic/thermal solar energy systems. Solar Energy 2007;81:1117-1131.

[13] Charalambous PG, Kalogirou SA, Maidment GG, Yiakoumetti K. Optimization of the photovoltaic thermal (PV/T) collector absorber. Solar Energy 2011;85:871-880.

[14] Alta D, Bilgili E, Ertekin C, Yaldiz O. Experimental investigation of three different solar air heaters: energy and exergy analyses. Applied Energy 2010;87:2953-2973.

[15] Kumar R, Rosen MA. A critical review of photovoltaic-thermal solar collectors for air heating. Applied Energy 2011;88:3603-3614.

[16] Tripanagnostopoulos Y, Nousia TH, Souliotis M, Yianoulis P. Hybrid photovoltaic/thermal solar system. Solar Energy 2002;72:217–234.

[17] Garg HP, Adhikari RS. Conventional hybrid photovoltaic/thermal (PV/T) air heating collectors: steady-state simulation. Renewable Energy 1997;11:363–385.

[18] Cox CH, Raghuraman P. Design considerations for flat-plate photovoltaic/thermal collectors. Solar Energy 1985;35:227–241.

[19] Kalogirou SA. Use of TRNSYS for modelling and simulation of a hybrid PV–thermal solar system for Cyprus. Renewable Energy 2001;23:247–260.

[20] Garg HP, Datta G, Bandyopadhyay B. A study on the effect of enhanced heat transfer area in solar air heaters. Energy Conversion and Management 1983;23:43-49.

[21] Sahin AD, Dincer I, Rosen MA.. Solar Energy Materials and Solar Cells 2007;91:53-159.

[22] Sopian K, Yigit KS, Liu HT, Kakac S, Veziroglu TN. Performance analysis of photovoltaic thermal air heaters. Energy Conversion and Management 1996;37:1657–1670.

[23] Othman MYH, Yatim B, Sopian K, Nazari Abu Bakar M. Performance analysis of a double-pass photovoltaic/thermal (PV/T) solar collector with CPC and fins. Renewable Energy Volume 2005;30:2005-2017.

[24] Othman MYH, Yatim B, Sopian K, Nazari Abu Bakar M. Performance studies on a finned double-pass photovoltaic-thermal (PV/T) solar collector. Desalination 2007;209:43-49.

[25] Ebrahim Ali Alfegi M, Sopian K, Othman MYH, Bin Yatim B. Experimental investigation of single pass, double duct photovoltaic thermal (PV/T) air collector with CPC and

fins. American Journal of Applied Sciences 2008;5:866-871.

[26] Velmurugan V, Gopalakrishnan M, Raghu R, Srithar K. Single basin solar still with fin for enhancing productivity. Energy Conversion and Management 2008;49:2602-2608.

[27] Ali Alfegi EM, Sopian K, Othman MYH, Bin Yatim B.. Mathematical model of double pass photovoltaic thermal air collector with fins. American Journal of Environmental Sciences 2009;5:592-598.

[28] Ho C-D, Yeh H-M, Chen T-C. Collector efficiency of upward-type double-pass solar air heaters with fins attached. International Communications in Heat and Mass Transfer 2011;38:49-56.

[29] Kundu B. Analytic method for thermal performance and optimization of an absorber plate fin having variable thermal conductivity and overall loss coefficient. Applied Energy Volume 2010;87:2243-2255.

[30] Omara ZM, Hamed MH Kabeel AE. Performance of finned and corrugated absorbers solar stills under Egyptian conditions. Desalination 2011;277:281-287.

[31] Holman JP. Heat Transfer. 10th ed., New York: McGraw-Hill Science; 2010,

[32] Duffie JA, Beckman WA. Solar Engineering of Thermal Processes. 3rd ed. New York: John Wiley & Sons; 2006.

[33] Zondag HA, de Vries DW, van Helden WGJ, van Zolengen RJC, van Steenhoven AA. The thermal and electrical yield of a PV–thermal collector. Solar Energy 2002;72:113–128.

[34] Huang BJ, Lin TH, Hung WC, Sun FS. Performance evaluation of photovoltaic/thermal systems. Solar Energy 2001;70:443–448.

[35] Tiwari A, Sodha MS, Chandra A, Joshi JC. Performance evaluation of photovoltaic thermal solar air collector for composite climate of India. Solar Energy Materials and Solar Cells 2006;90:175-189.

Biographies

Marc A. Rosen is a Professor of Mechanical Engineering at the University of Ontario Institute of Technology, where he served as founding Dean of the Faculty of Engineering and Applied Science from 2002 to 2008. Dr. Rosen has also served as President of the Engineering Institute of Canada and as President of the Canadian Society for Mechanical Engineering. Dr. Rosen is an active teacher and researcher in thermodynamics, energy technology, sustainable energy and the environmental impact of energy and industrial systems. Dr. Rosen has worked for such organizations as Imatra Power Company in Finland, Argonne National Laboratory near Chicago, and the Institute for Hydrogen Systems near Toronto. Dr. Rosen has received numerous awards and honours, including an Award of Excellence in Research and Technology Development from the Ontario Ministry of Environment and Energy.

Dr. Rakesh Kumar is actively involved in the research on solar thermal systems since 1992. He had completed his doctoral degree in Energy from prestigious Indian Institute of Technology Delhi. Dr. Kumar has contributed more than 35 research articles in Journals/Conferences and two book chapters on aee1pplied aspects of solar thermal systems. He was part of the research group involved on the development of national test standard for flat plate solar collectors rating. Dr. Kumar was also involved in many sponsored research project on solar dryer, solar cooker, solar distillation and photovoltaic-thermal systems for water/air heating in India & Canada. Most recently, he was part of research on solar thermal systems at CERL laboratory at University of Ontario Institute of Technology, Ontario, Canada.